Modeling

Modeling Options for Galveston Bay

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In recent years much concern has arisen in the environmental management community about the application of modeling to Galveston Bay and the need for an "accurate, state-of-the-art" model. However, there are disparate views as to exactly what properties such a model should have. Much has been made of, say, finite-differences versus finite-elements, or the need for three spatial dimensions, or whether a model is "cutting-edge" or "obsolete." Unfortunately, views are often aired as an exercise in polemics rather than science. Here we briefly review the various properties of models, especially in their significance for Galveston Bay, and survey the *computational* models that are presently extant. Then we dispense some philosophy as to what should and should not be considered in model selection. This is drawn from a research project presently underway under the sponsorship of Texas A&M Sea Grant.

The term "model" strictly refers to the mathematical formulation of a physical relationship. The jargon has evolved that applies the term to a computational scheme (derived somehow from a model in the first sense) implemented on a digital computer, frequently even a specific computer code. The term "model" will be used in all of these senses: hopefully context will clarify. There are many physical relationships of potential concern in estuarine management, many of which are interdependent. One physical process of central importance is the current velocity, which controls the transport of constituents, hence is one determinant of water quality. Moreover, in an estuary the current is very complex, being governed by irregular physiography, external forcing, and internal accelerations and dissipation. This survey will focus on circulation models, in order to keep the presentation bounded, and also because circulation modeling exemplifies the array of modeling possibilities (and controversies) for an estuary.

At the outset, we should recognize that any model is a simplification. The role of models in science is to sharpen concepts by simplification, by stripping a problem to its essential features to promote understanding. The point of departure in modeling is to decide what real-world features should, in fact, be modeled, and which, therefore, will be discounted as irrelevant. A model entails simplification from the pragmatic standpoint as well: without simplification, the mathematical solution would be impossible. The differences between models lie in how this simplification is achieved, i.e., what features are retained and what are sacrificed, and what aspects of the real world the simplified model depicts.

The first simplification concerns how much of the real world is to be treated. To comprehensively treat the circulation of Galveston Bay, we would have to include the dynamics of the Gulf of Mexico and the wind structure over the bay, which would then necessitate including the Atlantic Ocean and the atmosphere throughout the troposphere over the continental U.S., and each of these in turn would require treating the entire hemisphere. We draw a line, and bound the problem, (for example) to the physiographic domain of Galveston Bay itself. This now requires applying *boundary conditions* to close the mathematical solution. Here we will not pursue this aspect of modeling; however, we must observe that, though boundary conditions are frequently swept under the carpet as a matter of detail, in fact they are half of the problem. Specification is especially tricky for boundaries that are placed within the fluid domain (in contrast, for example, to a hard boundary like a shoreline), notably the ocean inlets and points of riverine inflow. In leaving this topic, we note that the boundary conditions control the answer: lousy boundary conditions applied to an otherwise sophisticated and accurate model yield lousy results.

Simplification can be applied at three different levels of formulation: conceptual, mathematical and computational. Generally, the conceptual simplifications are the most transparent and easy to evaluate because they explicitly state what kinds of features the simplified model will retain. Mathematical simplifications have the objective of expediting the mathematical solution of the problem, while maintaining fidelity to the conceptual model. This level of formulation includes the incorporation of specific mathematical expressions for different processes (which can include some conceptual simplification). Evaluation of a mathematical simplification is obviously more subtle than a simplification at the conceptual level, and may require some sophisticated analysis. Simplification at the third level, the computational, involves approximation to achieve a numerical solution. This is the snake pit of modeling. Theory is uneven, providing only guidance at best, evaluation is usually empirical hence case-specific, and the practice of art--even witchcraft--is prevalent.

Table 1. Simplifying postulates of watercourse circulation models.

Level of Acceptance in Scientific & Engineering Community		
Universal	Pretty Nigh Universal	Common
Newtonian, nonconducting	eddy formulation	parameterized eddy
	fluid	of turbulent fluxes
	coefficients	
Boussinesq approximation	neglect surface waves	Mannings "n"
hydrostatic balance	rotating plane	quadratic friction
incompressible		

Three separate principles can be exploited in formulating a model of a fluid system, *viz.* continuity, conservation of momentum, and conservation of mass. There are other, derivative principles (e.g., conservation of energy, enstrophy and vorticity), and sometimes the problem can be simplified so that two or more of these are rendered equivalent. The most primitive--i.e., unsimplified--mathematical statement of these principles is completely intractable, since it applies in full generality to any fluid (including gases and plasmas) in any condition anywhere. To specialize this statement for a natural water body on the earth entails some major simplifications; the acceptance of these by scientists in the field ranges from universal to spongy.

Table 1 lists some of these simplifications and their relative level of acceptance.

We have not yet differentiated estuaries: these considerations can apply as well to oceans, lakes and rivers. These simplifications get us to the "primitive equations" of estuary hydrodynamics, a set of simultaneous partial differential equations in three spatial dimensions and time, which are still a long way from being soluble. Table 2 shows examples of further simplification, for each level of formulation, that appear in the estuarine modeling literature. There are many others, of course. The first column, the conceptual, which further simplify the primitive equations, are the most important because these *ab initio* limit the range of applicability of the model.

Table 2. Simplifications used in estuary circulation models.

	Level of Formulation	
Conceptual	Mathematical	Computational
kinematic only	linearize	discretization:
steady-state	dispersion model of	finite-difference
average in space	advective fluxes	finite-element
simple geometry	spectral expansion	boundary-element
horizontally nondivergent	basis expansion	truncated spectrum
constant density	transformed coordinates (e.g.,	basis-expansion
antitriptic flow	sigma & boundary fitting)	truncation
transport-dominated	altered order (e.g, vorticity)	timestepping
non-rotating earth	irrotational	grid system (i.e.,
barotropic flow	mode-splitting	nodal network)
zero inertia	local acceleration only	

In Table 3 are presented some estuary models that are on-the-market, i.e., fully operational and whose codes have been transported to other users. This list is certainly not exhaustive but is intended to exemplify what is available. Several observations may be made:

1. There are a number of "three-dimensional" models, and with modern computational resources, the development of a solution for some form of the three-dimensional model has become routine;

2. Of the 11 models listed, there is a duplication in only two of all of these features, viz. the Princeton and TAMUG. There are, of course, other features of the models not tabulated, and in which these two differ;

3. There are seven different applications for Galveston Bay;

4. Only one of these models is presently capable of operation on a microcomputer; and

5. Only one of these would I describe as "obsolete" in the pejorative sense, i.e., whose utility is significantly degraded compared to other products that can be employed at an equivalent economic burden, namely the EPA DEM.

Table 3 . Some operational estuary models and selected properties (* indicates existing application for Galveston Bay).

Name or Source	Dimensions	Time Variability	Variable Density	Coupled Density	Current Calculation	Computation Horizontal	Computation Vertical	Computer Resources
EPA DEM Orlob-Shubinski	1 linked	transient	no	no	dynamic	FD	--	MF, mini
*GBP/TWDB	2	transient	no	no	dynamic	FD	--	MF, mini
*TWDB (Gray-Lynch)	2	transient	yes	yes	dynamic	FE	--	MF, mini
*WES TABS-RMA-2V	2	transient	yes	no	dynamic	FE	--	MF, mini
*NOS COMPAS (Galt-Klein)	2	steady	no	no	kinematic	FE	--	micro
*WES TABS-RMA-10	3	transient	yes	yes	dynamic	FE	FE	Cray, MF
WES CH3D (Sheng)	3	transient	yes	yes	dynamic	FD[1]	FD[2]	Cray, MF
*USGS (Walters)	3	spectral	yes	yes	dynamic	FE	expansion	mini, large micro
Princeton (Mellor-Oey)	3	transient	yes	yes	dynamic	FD	FD	MF,mini
Princeton (Mellor-Blumberg)	3	transient	yes	yes	dynamic	FD[3]	FD[2]	MF,mini
*TAMUG (Whitaker)	3	transient	yes	yes	dynamic	FD[3]	FD[2]	mini

[1] Stretched coordinates

[2] Sigma coordinate

[3] Boundary-fitting orthogonal curvilinear coordinates

How should one chose a model among this variety? There are two (mutually exclusive) criteria which seem to be widespread: (1) the most complicated model available--fully transient three-dimensional coupled nonlinear--because it is most accurate; (2) the model that is easiest to operate. I submit that neither is valid.

Model selection should proceed from an analysis of the problem of concern, i.e., what is required of the model in the management context, to determining which real-world processes control that problem, and what information base is available for their delineation.

Requirements include: parameters (nitrogen species, coliform bacteria, BOD, salinity), time resolution (seasonal, daily, long-term average), space resolution (detailed structure at a ten m resolution, averages over several km area), vertical resolution (vertical average, profiles at one m interval), and accuracy. Examples of controlling variables and/or processes include: geometry/physiography, tides, freshwater inflow, waste discharge flows, detention time ("flushing"), meteorological-driven responses, density currents, horizontal transports, kinetics, and vertical mixing. The management question must be properly articulated. Models can clarify this articulation process, which in many instances will be interactive and empirical, involving the application of a model

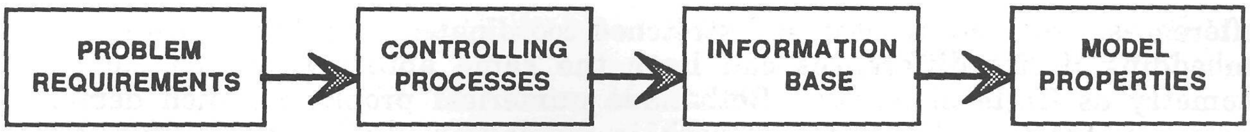

Figure 1. Selection sequence.

itself. (Indeed, one may have to operate a model to refine the criteria for selecting a model.) How will the results actually be applied in a management context? Can you really discriminate the difference in effects of a one ppm change in organic nitrogen, say, or a one ppt change in salinity? For many management issues, the policy options are robust, not significantly affected by a 25% (say) improvement in parameter accuracy. Different management questions may require different models, and there remain many important problems that can be adequately treated by rather simple models. In this case, a more complex model, in better mirroring the real world, usually complicates the enterprise. A more fundamental question is whether the important physical/kinetic processes are represented properly. A correctly formulated 2-D model is superior to an incorrectly formulated 3-D model.

A related but separate aspect of model selection is the existing information base. Any model application is also limited by the level of accuracy in the input data. For example, if one has only long-term average wasteloads or inflows, then one is limited to analyzing only long-term average concentrations. If the management question requires a finer level of resolution, then the process is at an impasse, until a more detailed information base becomes available. While a model can help delineate the limits imposed by the present information base, it cannot substitute for an information base (contrary to what seems to be a popular belief). This is particularly important in applying a three-dimensional model. For example, the internal vertical stresses and transports must be explicitly computed, whereas they are averaged out in the two-dimensional model. The surface and bottom of the water column become boundaries, where conditions must be carefully specified.

The fact that there are a number of models operational and potentially applicable to Galveston Bay does not imply that the modeling problem is solved. On the contrary, there are aspects of each of these models that are unsatisfactory or unproven. In this context, brief mention should be made of the need for verification of any candidate model against field data representative of the scales and processes of concern. The many levels of simplification involved (Table 2) can entail departure from reality, no matter how reasonable the simplifications seem, so the model must be tested. In addition, there is a considerable latitude for errors, which can be exposed during verification. (There is also the need for calibration, if there are free parameters in some of the mathematical formulations. Calibration does not replace verification.)

Numerical methods, in this writer's view, have probably been overemphasized in model development, relative to physical processes. Much has been made of the differences between finite-difference and finite-element integrations. With interactive grid generators, finite elements are now as flexible as finite differences. With curvilinear and stretched coordinates, and techniques of grid-embedding, finite differences can have the same ability to depict complex geometry as finite elements. Both have numerical problems which demand careful attention. Much more work is needed in the basic physics, both observationally and theoretically. How to handle the inlet boundary condition remains a major problem. Bed friction, though commonly accepted as quadratic with a coefficient, has memory and inertia, and can be directed other than opposite to the current, and needs better formulation. The depiction of nonadvective fluxes, both dispersion and turbulence, is a basic weakness of all of these models.

Hydrodynamic and Salinity Studies of the Galveston Bay System

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The U.S. Army Corps of Engineers, Galveston District, is sponsoring field studies and numerical model studies of the Galveston Bay system as part of the investigations for the supplemental environmental impact statement to the Houston-Galveston Navigation Channels Project. Some of these studies are being conducted by the Hydraulics Laboratory at the Waterways Experiment Station (WES), Vicksburg, MS.

Germane aspects of these studies to this workshop are the long-term (180 days) instrument deployment in the bay and the verification and application of a three-dimensional (3-D) numerical model of the bay hydrodynamics. The field studies occurred between July, 1990 and January, 1991 with analysis of the data to be completed during the summer of 1991. The data from these field investigations, which consists of salinity, temperature, current, and water level measurements, are to be used to verify the 3-D numerical model. Verification of the numerical model is scheduled for completion in January, 1992 and applications of the model are to be completed by April, 1992. The model will be used to determine any impacts of the proposed Houston-Galveston Navigation Channels Project on bay salinities and currents.

The long-term instrument deployments consisted of six water level recorders, of which three also recorded salinity and temperature, six salinity meters, and eight current/salinity/temperature meters. The data collection program was supplemented by several water level recorders and salinity/temperature instruments operated by the Texas Water Development Board, Texas Parks and Wildlife Department, U.S. Geological Survey, and National Ocean Service, National Oceanic and Atmospheric Administration. For approximately the first three months, instruments were deployed to obtain currents, salinities, and temperatures in the Houston Ship Channel and to obtain salinities and water levels bay-wide. For the last three months, some instruments were redeployed to emphasize measurements along a line into Trinity Bay perpendicular to the Houston Ship Channel. Also, for the last three months, single current meters were deployed in East and West Bays. In conjunction with these field studies, a wind (direction and magnitude) station was located in the central bay near Redfish Bar.

The method of instrument deployment allowed characterization of relevant hydrographic parameters in Galveston Bay through long-term measurements at a typical frequency of ten minutes. These data will provide the major source of verification for the numerical model study, and of themselves, these data are a valuable source of information describing bay-wide conditions during the last six months of 1990.

An interesting portion of the field investigation was the deployment of the WES Estuarine Boundary-layer Instrumentation System (EBIS) in Galveston Bay.

Environmental concerns of enhanced salinity movement near the bay bottom resulting from ship-induced mixing in the Houston Ship Channel can be uniquely addressed with the EBIS. The EBIS is a tripod device developed in a research program at WES, which is equipped with an array of probes to measure pressure, temperature, turbidity, bed shear stress, and salinity. The EBIS was designed specifically for near-bed measurements in an estuarine environment, and most of the probes may be remotely controlled to measure at depths from essentially at the bed surface to one meter above the bed. A sampling frequency of five seconds was used, which allowed measurement of short duration, dynamic changes. The EBIS was deployed on two occasions for one-two days each approximately two-hundred feet from the Houston Ship Channel in the vicinity of Redfish Bar. Short-term changes in salinity (over several minutes) and pronounced velocity and water level changes coincident with ship passages were recorded. The salinity changes were a function of ship size, ship direction (inbound or outbound), and ambient current direction (flood or ebb). The salinity change, which could be either an increase or decrease, was recorded as a rapid response of as much as three ppt that gradually returned to near pre-event levels within ten minutes or less. Final results and conclusions from the EBIS deployment will be available in mid-1991.

The 3-D numerical model to be applied to Galveston Bay is RMA-10, which was initially developed by Dr. Ian King of Resource Management Associates, Inc., and the University of California at Davis (King, 1988). The model solves the 3-D equation of motion and transport of salt and temperature using the finite element method. The flexibility of RMA-10, which allows specification of one-dimensional, two- dimensional in the horizontal plane, and three-dimensional computational elements, will be fully used in this application. Tidal streams and rivers will be represented in one dimension, shallow bay areas in two dimensions, and the deep-draft channels and adjacent areas in three dimensions. RMA-10 will predict time-varying currents, salinities, and temperatures in Galveston Bay as influenced by time-varying boundary conditions of wind, freshwater inflows, and tides from the Gulf of Mexico. Modification to appropriate model input data will allow different channel widths and depths to be represented as proposed in the Houston-Galveston Navigation Channels Project or other bathymetric changes, if desired.

For this study, the Galveston Bay model will be used to assess changes in salinities and currents for various freshwater inflow conditions (present, 1995, 2020 and 2050 hydrologies) in conjunction with the bathymetric changes of the proposed channel improvements. The flexibility of the finite-element code will also be used to accurately represent and evaluate several beneficial use plans of dredged material, which are to be considered as part of the project. Model results will be made available to determine impacts to oysters in Galveston Bay. This will occur either through linkage of the RMA-10 code to an oyster population dynamics model or through direct analysis of results form RMA-10.

In conclusion, the model will provide a characterization of the response of bay salinities and currents to a number of important external parameters and forcing. The model can be used to evaluate the response of bay salinities and currents to the location and magnitude of freshwater inflow, wind, tidal forcing from the gulf, bay bathymetry, and changes to bathymetry. The field investigations provided data to characterize the bay during a 180-day period and to allow numerical model verification.

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The COMPAS Screening Model for Galveston Bay

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The National Ocean Service (NOS) Strategic Assessment Branch of NOAA has developed general planning software called the Coastal Ocean Management, Planning and Assessment System (COMPAS). The NOS and the Texas Water Commission (TWC), together with several other state agencies, have undertaken a project to implement COMPAS on the Texas bays, the first one of which will be Galveston Bay. This system is microcomputer-based (specifically, the Macintosh) and is designed to be an adjunct in comparative studies of estuaries and in formulating management strategies for dealing with these systems. It includes data bases on nutrient loads, fishery distributions, contaminant discharges, and sediment types.

A central feature of COMPAS is a circulation model that depicts tidal, dispersive and residual (i.e., long-term mean) transports throughout the estuary. The model has the following properties:

1. The model is two-dimensional in the horizontal plane (i.e., vertically integrated);

2. The model is based on the numerical solution to the continuity equation, subject to boundary conditions, using the finite-element method;

3. The model explicitly depicts irregular bathymetry and physiography by use of finite elements;

4. The transport vectors (currents) are input directly to a mass-transport model for delineation of contours of various constituents, including salinity; and

5. Nonadvective transport is modeled with dispersion coefficients. However, some advective processes that are traditionally modeled by dispersion coefficients, such as salinity intrusion, can be explicitly treated.

The computation is based upon a diagnostic model developed by Jerry Galt and his associates at NOAA (e.g., Galt, 1980, Klein and Galt, 1985). The model has been applied to several estuary systems, as well as larger coastal watercourses, such as the Gulf of Mexico (during the Ixtoc spill). It is important to emphasize that the currents are kinematic predictions, not dynamic. That is, the currents are derived from a stream function that is consistent with boundaries and known flows (such as freshwater inflow, tidal prism, etc.), but not directly based on the forces which produce those currents.

The chief advantages of the model are its elegance and simplicity while achieving fidelity to the irregular physiography of the bay. It is computationally efficient and runs on the microcomputer, therefore can be used almost interactively. The model allows one to apply one's intuition and external qualitative knowledge directly to constrain the interior transports. This can be either an advantage or a limitation, depending upon how adequately the circulation is understood qualitatively, and whether this level of accuracy is adequate for the problem at hand. In its present state of development, explicit circulations are incorporated for: (1) freshwater through flow due to the San Jacinto, Trinity and Chocolate Bayou (in West Bay); (2) cooling water circulations due to P.H.Robinson and Cedar Bayou S.E.S.s; (3) density-driven circulation associated with the Houston Ship Channel; and (4) tidal influx through the system, including attenuation at the mid-bay constriction.

Application in the management of Galveston Bay is most suited to large-scale concerns, e.g., evaluating wasteload impacts, freshwater diversion effects, and alterations in habitat quality. The model is a "screening tool," and this is an accurate appraisal of how it should be used in management of Galveston Bay, *viz.* in large-scale "what-if" evaluations of various scenarios, and as a preliminary quantitative impact analysis. There are problems for which it is ill-suited, e.g., counter-intuitive processes that must be accurately evaluated dynamically, such as alterations in salinity intrusion due to dimension changes in a ship channel or very fine-scale gradients in concentration in specific regions. Nor is the model suited for very transient events such as flood hydrographs, though it is useful for simulating long-term variations in inflow (seasonal effects, for instance).

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Three-Dimensional Circulation and Salinity Transport Model of Galveston Bay

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The present study is to apply a curvilinear three-dimensional multi-layered estuarine and coastal model to perform simulation of the three-dimensional flow process of the Galveston Bay and to predict the salinity distributions. Galveston Bay is an extremely complex and dynamic estuarine system, not only due to the high variability of a number of physical mechanisms, but also to the important social, ecological and economic issues that are present. This estuary serves a number of functions, e.g., nursery and adult habitat for commercial fishery species, flood control for coastal communities, pollution control for the surrounding coastal environments, transportation, and recreation. Besides the economic function of the Houston Ship Channel, Galveston Bay has been described as highly productive in terms of both oyster and shrimp markets. It is widely noted that oyster productivity is greatly influenced by estuarine salinities. In large part, this productivity is associated with the exclusion of marine predators that are intolerant of low and fluctuating salinities.

Wind stresses, freshwater inflows, tides, bathymetry, the coastal forces from the continental shelf, and even shipping all effect the circulatory patterns, salinity distributions, nutrient and detrital transport, and pollutant flushing. The bay's ability to perform its natural functions may be impaired by human uses of the bay. Also, the reduced water quality due to the increase of transportation, land development and the releasing of pollutants into the bay environment have a high possibility of damaging the ecosystem of the bay. The impact of oil spills to this estuarine system is another major issue to be considered. All these problems in Galveston Bay have shown the need for extensive study to understand the impacts of hydrodynamic, environmental, and ecological influences for the whole estuarine system.

Hydrodynamic modeling is an important aspect of the Galveston Bay study. Results of modeling efforts will describe the circulation patterns of the system and act as a driver for salinity transport as well as water quality and ecological models. Shankar and Masch (1970) have applied a simplified two-dimensional model to study the salinity variation of Galveston Bay under the influences of freshwater inflows and tide. However, the important factors of nonlinear diffusion and baroclinic terms were neglected during their modeling efforts. Also, the two-dimensional simulation cannot provide the complete flow process of Galveston Bay, because three-dimensional variation, in terms of velocities and salinity, are active in the system.

The objective of this study is to develop a three-dimensional hydrodynamic model of Galveston Bay. This model will be solved to determine the three-dimensional velocity field and salinity distributions for the whole bay. The basic equations for governing the three-dimensional flow field and salinity distribution are the Navier-Stokes equations and salinity transport equation. To facilitate the applications of the boundary conditions on the bounding surface and to resolve the complex geometry more smoothly, a curvilinear coordinate transformation technique is adopted. This model solves full Navier-Stokes equations in a curvilinear-grid system, where the nonlinear, diffusion, baroclinic and coriolis terms are included. The influences of wind, tides, freshwater inflows, bathymetry are considered in this model.

The model developed for the work is a three-time-level implicit scheme finite-difference model. A staggered grid is used in both the horizontal and vertical directions of the computation domain. Mode splitting technique is applied to assure that the computation of the external free-surface elevation is separated from solving the three-dimensional equations. The free-surface elevation and vertically-integrated velocities (or two-dimensional velocities) are computed first from the vertically-integrated equations (external mode) by using ADI method. Following this, the three-dimensional velocities are then solved using a vertically-implicit scheme. The vertical turbulent mixing coefficients in this model are calculated by means of a simplified second-order turbulence closure model. With known velocity field, the salinity distributions will be obtained by solving the salinity transport equation.

The appropriate boundary conditions and initial conditions are provided for model simulation. At the free-surface, the wind stress is prescribed and the salinity flux is zero. At the bottom, a quadratic stress law with drag coefficient based on the logarithmic velocity profile is used, while the salinity flux is zero. Along the lateral boundaries, discharges of freshwater inflows are specified at the stream boundaries, while the surface elevation and salinity are specified at the tidal entrances. The salinity at the open boundary can be allowed to change according to inflow and outflow in this model.

By inputting bathymetry of Galveston Bay, freshwater inflow, tides and wind data into the model, the three-dimensional time variation of the circulation patterns, free-surface elevation and salinity profiles will be obtained to describe this dynamic system. The impacts of velocity and salinity field due to changing the freshwater inflows and wind stresses will be analyzed. The influence of bathymetry to the circulation field is also of interest to study. The tidal and freshwater inflow discharges (from Dickinson Bayou, Double Bayou, Clear Creek, Trinity River, Cedar Bayou, Goose Creek and San Jacinto River) used in Shankar and Masch's study with assumed wind stresses are employed for the initial simulation to predict velocity field and salinity profiles. Model calibration and validation based on the field measurements will be further conducted. After analyzing these numerical results, a thorough understanding of the hydrodynamic impacts on Galveston Bay will be developed.

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